BELLCOMM, INC.
955 L'ENFANT PLAZA NORTH, S.W. WASHINGTON, D.C. 20024

B70 10044

SUBJECT: Manual TLI Engine Cutoff Calculation - Case 310

DATE: October 21, 1970

FROM: D. R. Anselmo
L. P. Gieseler

ABSTRACT

Beginning with Apollo 15, in the event of a crew take-over during translunar injection the crew will manually provide attitude control and the spacecraft computer will determine engine cutoff time based on a predetermined velocity magnitude. A Bellcomm simulation of the cutoff algorithm currently employed by MSC has demonstrated that for a nominal attitude profile the cutoff time prediction results in a velocity magnitude error of about 1 fps. Attitude profile deviations will produce a cutoff altitude error which results in a velocity magnitude error for a required translunar energy. A velocity error of about 5 fps is produced for each nautical mile of altitude error. Based on limited, preliminary crew simulations, the expected error in altitude will produce a velocity magnitude error on the order of 15-20 fps.

A possible alternative cutoff calculation which is altitude dependent has been investigated. This improved formula reduces the error to about .5 fps for each nautical mile of altitude error. This would reduce the expected velocity magnitude error to 1.5 - 2 fps.

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MEMORANDUM FOR FILE

A relatively simple algorithm for the calculation of the S-IVB cutoff time in the event of a manually guided trans-lunar injection is being implemented in the spacecraft computer beginning with Apollo 15. The cutoff algorithm was tested at Bellcomm to determine the expected cutoff time errors resulting from this calculation. Preliminary simulations of nominal TLI recently performed at MSC have produced cutoff errors on the order of 20 fps in the velocity magnitude.

The current prediction of cutoff time for achieving a specified velocity magnitude is simply:

$$T_{go} = \frac{V_{Required} - V_{now}}{a} \tag{1}$$

where acceleration, a, is approximated by

$$a \cong \frac{|V_{now}| - |V_{2\ sec\ ago}|}{2} \tag{2}$$

and $V_{Required}$ is the required velocity magnitude at cutoff, computed by

$$V_{Required} = \left(2E + \frac{2\mu}{R_{co}} \right)^{1/2} \tag{3}$$

where E is the desired energy, R_{co} is the nominal cut-off radius and μ the gravitational constant of the earth.

When T_{go} reaches four seconds the cutoff sequence is initiated. Therefore, the accuracy of the calculation at four seconds to go to cutoff is the primary concern.

In the current implementation $V_{Required}$ is calculated pre-burn based on the achieved earth orbit and a pre-burn simulation of TLI. This calculation will produce a $V_{Required}$ that is in error when the altitude at cutoff is different from the pre-burn simulation. The sensitivity is about 5 fps error in the actual cutoff velocity (V_{co}) per nautical mile error in altitude.

Two types of errors should be distinguished. First, if the true $V_{Required}$ is known, there is an error in predicting the exact cutoff time due to changing acceleration during the 2-second computation cycle. Second, there is an error in the calculation of $V_{Required}$ due to a cutoff altitude error. For the current implementation, if no altitude error is introduced, only errors of the first type are introduced. It will be shown that this is negligible. The second error type, namely altitude error, does produce significant errors in the calculation of the $V_{Required}$.

To improve the accuracy of $V_{Required}$ in the presence of altitude errors, the calculation could be performed in the spacecraft computer using the current value of R. The algorithm presented here does this and, further, includes a correction for the altitude rate. The quantity $R_{now} + T_{go}\,\dot{H}_{now}$ replaces R_{co} in Equation 3 where R_{now} is the current radial distance, and $\dot{H}_{now}$ is the altitude rate. The algorithm then becomes

$$T_{go} = \frac{V_{Required\ at\ R_{now}} - V_{now}}{a + C} \tag{4}$$

$$C = \frac{\mu\,\dot{H}_{now}}{\left(V_{Required\ at\ R_{now}}\right)\left(R_{now}\right)^2} \tag{5}$$

$$V_{\text{Required at } R_{now}} = \left(2E + \frac{2\mu}{R_{now}} \right)^{1/2} \qquad (6)$$

This formulation behaves exactly as the current algorithm as far as errors of the first type are concerned. Details of the derivation of these equations are given in the Appendix.

Results

A nominal trajectory was simulated, and T_{go} was calculated every two seconds using both the current and the improved algorithms. The S-IVB pitch rate was then varied to produce two dispersed trajectories having altitude errors of ±3 nm at TLI cutoff. The error in cutoff time was computed by subtracting the actual time to cutoff from the predicted time, T_{go}. The cutoff velocity magnitude error that would result was computed by multiplying the error in T_{go} by the tangential acceleration, which equaled about 40 ft/sec^2. The results are plotted in Figures 1 and 2 for the nominal and the dispersed trajectories respectively.

As shown in Figure 1 the error for the nominal trajectory at 4 seconds before cutoff is about .025 seconds or about 1 fps. At 8 seconds before cutoff the error rises to about .1 second or 4 fps. The current algorithm is slightly better than the improved one for the nominal trajectory. This is understandable since the current algorithm uses the exact value for R_{co} in Equation 3, whereas in the improved algorithm this is approximated by $R_{now} + \dot{H}_{now} T_{go}$. This is an error of the first type, due to changing acceleration, and is essentially the same for both formulations.

As shown in Figure 2 the error for the dispersed trajectories at 4 seconds before cutoff using the current algorithm equals .42 seconds or 16 fps and -.36 seconds or -14 fps for the high altitude and low altitude trajectories respectively. The error using the improved algorithm is reduced to .03 seconds or 1.2 fps.

Conclusions

The present algorithm for predicting the cutoff time gives good results when the cutoff altitude equals the nominal altitude. When altitude errors are present, the cutoff velocity magnitude will be in error by about 5 fps for each nautical mile of altitude error. An improved formula has been developed which takes altitude errors into account. The error using the improved formula can be reduced by about a factor of 10.

D. R. Anselmo

L. P. Gieseler

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Attachments

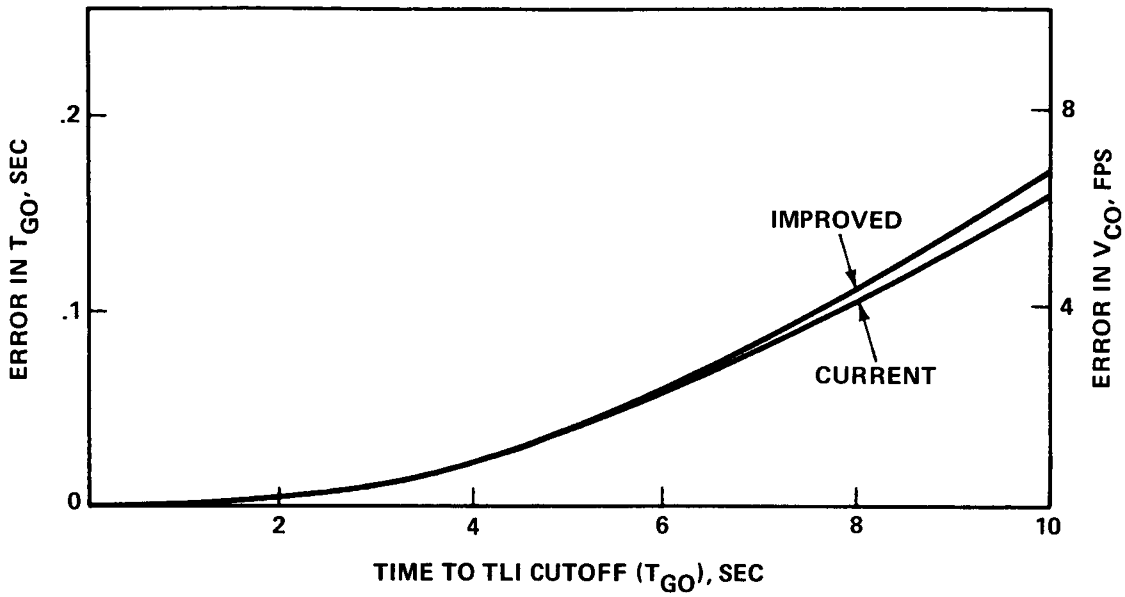

FIGURE 1 - ERRORS FOR NOMINAL TRAJECTORY

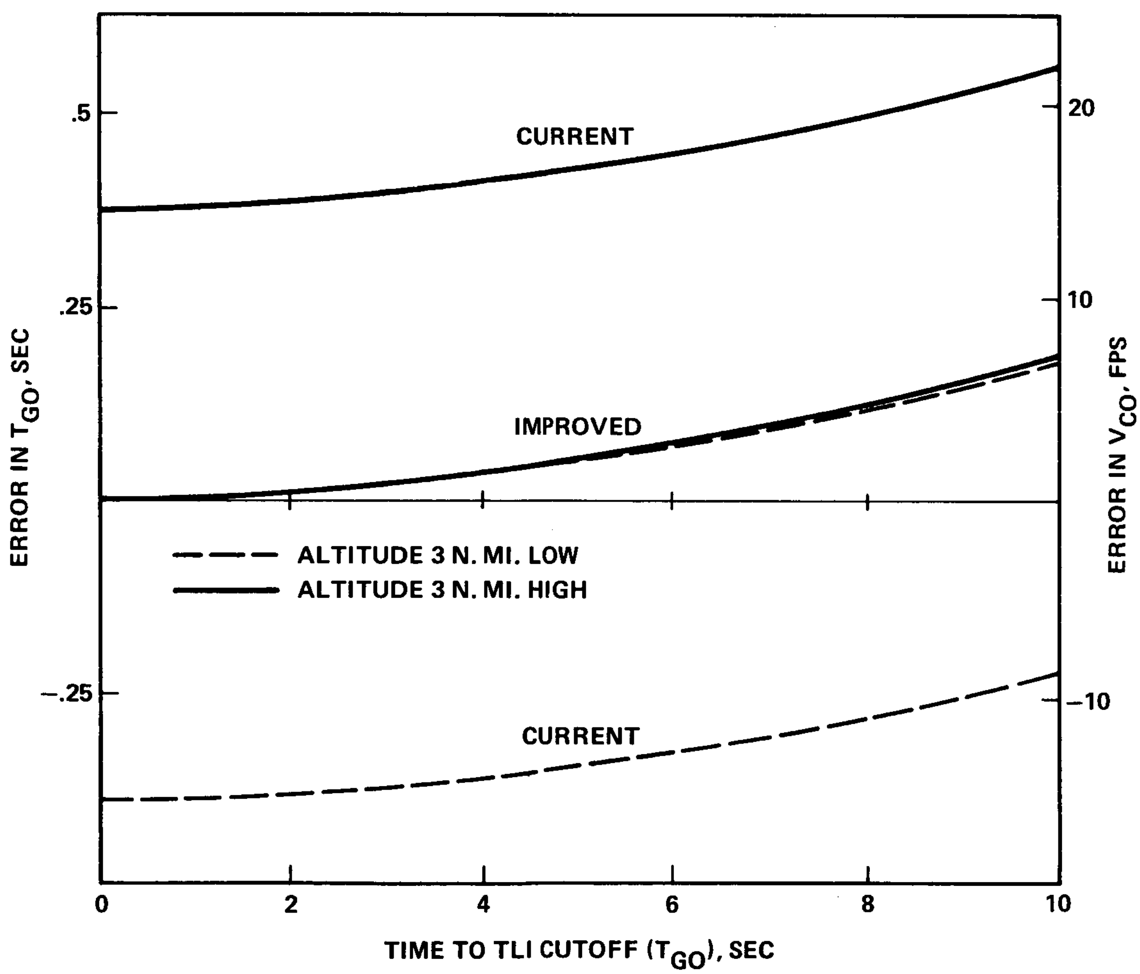

FIGURE 2 - ERRORS FOR DISPERSED TRAJECTORIES

APPENDIX

Derivation of Equations 4 and 5

From Equation 3,

$$V_{Required} \cong \left[2E + \frac{2\mu}{R_{now} + T_{go}\, \dot{H}_{now}} \right]^{1/2}$$

$$\cong \left[2E + \frac{2\mu}{R_{now}} - \frac{2\mu\, T_{go}\, \dot{H}_{now}}{\left(R_{now}\right)^2} \right]^{1/2}$$

$$\cong \left[\left(V_{Required\ at\ R_{now}} \right)^2 - \frac{2\mu\, T_{go}\, \dot{H}_{now}}{\left(R_{now}\right)^2} \right]^{1/2}$$

$$\cong V_{Required\ at\ R_{now}} - \frac{\mu\, T_{go}\, \dot{H}_{now}}{\left(V_{Required\ at\ R_{now}}\right)\left(R_{now}\right)^2}$$

From Equation 1,

$$T_{go} = \frac{V_{Required\ at\ R_{now}} - V_{now} - \dfrac{\mu\, T_{go}\, \dot{H}_{now}}{\left(V_{Required\ at\ R_{now}}\right)\left(R_{now}\right)^2}}{a}$$

Solving for T_{go},

$$T_{go} = \frac{V_{\text{Required at } R_{now}} - V_{now}}{a + C} \tag{4}$$

where
$$C = \frac{\mu \dot{H}_{now}}{\left(V_{\text{Required at } R_{now}}\right)\left(R_{now}\right)^2} \tag{5}$$

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